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X.

DAMPENING OF ELECTRICAL OSCILLATIONS ON IRON WIRES.

By John Trowbridge.

Presented May 27, 1891.

It has generally been assumed by those who have studied the subject of very rapid oscillations of electricity, such as occur in Leyden jar discharges, that the magnetic character of the conductor has very little influence upon the character of the discharge. Thus, in a note to an article on electrical waves, W. Feddersen states that electrical oscillations may suffer a slight weakening on iron; but this diminution is very slight: —

"Beim Eisen könnte in Folge der Magnetisirungen eine Abweichung hervortreten; in dess zeigt der Versuch, dass dieselbe keinenfalls bedeutend ist, übrigens in dem Sinne erfolgen müsste, als wenn die Elektricität beim Eisen ein grössere Hinderniss fände, wie bei den übrigen Metallen." *

In Dr. Lodge's treatise on Modern Views of Electricity (ed. 1889), we find the following: —

"But in the case of the discharge of a Leyden jar iron is of no advantage. The current oscillates so quickly that any iron introduced into its circuit, however subdivided into thin wires it may be, is protected from magnetism by inverse currents induced in its outer skin, and accordingly does not get magnetized; and so far from increasing the inductance of the discharge circuit, it positively diminishes it by the reaction effect of these induced currents; it acts, in fact, much as a mass of copper might be expected to do." (p. 365.)

Fleming writes as follows: —

"With respect to the apparent superiority of iron it would naturally be supposed that, since the magnetic permeability of iron bestows upon it greater inductance, it would form a less suitable conductor for discharging with great suddenness of electric energy. Owing to the fact that the current only penetrates just into the skin of the conductor,

* Annalen der Physik und Chemie, No. 108, 1859, p. 499.

there is but little of the mass of the iron magnetized. Even if these instantaneous discharges are capable of magnetizing iron, . . . the electromotive impulses or sudden rushes of electricity do not magnetize the iron, and hence do not find in it any greater self-inductive opposition than they would find in a non-magnetic but otherwise similar conductor. Dr. Lodge's further researches seem to show that there is a real advantage in using iron for lightning conductors over copper, and that its greater specific resistance and higher fusing point enables an iron rod or tape to get rid safely of an amount of electric energy stored up in the dielective which would not be the case if it were copper." *

Fleming describes in full Dr. Lodge's experiments to prove the non-magnetizability of iron by sudden discharges: —

"In the experiments on alternative path, as described by Dr. Lodge, the main result is very briefly summed up by saying that, when a sudden discharge had to pass through a conductor, it was found that iron and copper acted about equally well, and indeed iron sometimes exhibited a little superiority, and that the thickness of the conductor and its ordinary conductivity mattered very little indeed. . . . In the case of enormously rapid oscillations the value of the impulsive impedance varies in simple proportion to the frequency of the oscillations, and depends on the form and size of the circuit, but not at all on its specific resistance, magnetic permeability, or diameter. . . . For discharges of a million per second and upwards, such as occur in jar discharges and perhaps in lightning, the impedance of all reasonably conducting circuits is the same, and independent of conductivity and permeability, and hardly affected by enormous changes in diameter." †

Turning now to the observations of Hertz, we find it stated that the material, the resistance, and the diameter of the wire of the micrometer circuit employed by him, have very little influence on the result. The rate of propagation of an electrical disturbance along a conductor depends mainly on its capacity and coefficient of self-induction, and only to a small extent on its resistance. Hertz concludes that, owing to the great rapidity of the alternations, the magnetism of the iron is unable to follow them, and therefore has no effect on the self-induction. When a portion of the micrometer circuit employed by Hertz was surrounded by an iron tube, or replaced by an iron wire, no perceptible effect was obtained, and thus the result was apparently

* Fleming, Induction of Electric Currents, p. 398. † Ibid., p. 411.

confirmed that the magnetism of the iron is unable to follow such rapid oscillations, and therefore exerts no appreciable effect. The velocity of propagation in a wire has a definite value independent of its dimensions and material. Even iron wires offer no exception to this, showing that the magnetic susceptibility of iron does not play any part in the case of such rapid motions.*

Although the impulsive impedance is apparently not affected by the magnetic character of the wire, experiments lead me to believe that discharges of the quick period of a Leyden jar are affected very appreciably by the magnetic nature of iron, steel, and nickel conductors. This effect is so great that it dampens the electrical oscillations, and makes it difficult to determine whether the time of oscillation is also affected by the permeability of the conductor.

The apparatus employed was similar to that described in the investigation of electrical oscillations with an air condenser.† Certain important modifications, however, were made. The plane mirror which was used in the former research was replaced by a concave mirror of ten feet focus and three and a half inches in radius. This mirror was mounted upon the end of the armature shaft of a one-half horse-power electric motor.

The discharging apparatus consisted of a sharp cutting tool, insulated, and mounted on the edge of the rotating disk bearing the mirror. It was metallically connected with a grooved ring of brass mounted upon the shaft and insulated from it by hard rubber. Around this was wound a copper wire, one end of which was connected with the discharging wire, and the other drawn taught by a rubber band. The electrical discharge was thrown on to the circuit by thrusting forward a lever which brought a solid hinged frame containing a strip of soft type-metal into contact with the rapidly revolving steel cutting tool. An electrical contact was thus insured by the tool cutting a groove in the strip of type-metal. In order to avoid a spark at the contact, the type-metal was thickly covered with a wax of peculiar composition. The only spark that occurred, therefore, was the one the oscillations

* "Ersetzen wir den bisherigen Kupferdraht durch einen dickeren oder dünneren Kupferdraht oder durch einen Draht aus anderem Metall, so behalten die Knotenpunkte ihre Lager bei. Die Fortplanzungsgeschwindigkeit in allen solchen Drähten ist daher gleich, und wir sind berechtigt, von derselben als einer bestimmten Geschwindigkeit zu reden. Auch Eisendrähte machen keine Ausnahme von der allgemeinen Regel, die Magnetisirbarkeit des Eisens kommt also bei so schmalen Bewegungen nicht in Betracht." — Ann. der Physik und Chemie, No. 34, 1888, p. 558.

† These Proceedings, Vol. XXV. p. 109.

of which I desired to study. At each trial the type-metal was moved so as to expose a new cutting surface. The type-metal was insulated from the rest of the apparatus, but connected with the outer coating of the Leyden jar; first both terminals of the Holtz machine were thrown off, and immediately after the cutting tool, ploughing its way through the type-metal, placed the outer coating of the Leyden jar in circuit with one of the two parallel wires leading to the terminals of the spark. The other wire was permanently in connection with the inner coating of the jar.

Beside the short lead wires above described, the discharging circuit consisted of two parallel wires 30 cm. apart and 510 cm. long. These were the only portions of the apparatus changed during the experiment, and they were replaced by wires of different material and of different size. The other conditions — length of spark, lead wires, and the copper cross wire connecting the outer end of the long parallel wires — remained undisturbed throughout the experiment.

The Leyden jar was charged each time as nearly as possible to the same potential, judging by the number of turns given the Holtz machine. It is unfortunate that no more accurate means of measuring it were at hand, although the different negatives showed but slight variation. The capacity of the jar to alternations of this period was 5060 electrostatic units.

I describe the discharging portion of the apparatus minutely, for the success of an investigation of this nature depends upon the suppression of all sparks save that which one wishes to observe; and the method surely and completely accomplished this. The photograph of the spark could thus be made to fall very accurately on the sensitive plate. When one considers that the image of the spark was flying through the air on a circle of a radius of ten feet with a velocity of a mile a second, it will be seen that an extremely small deviation in the point of contact between the cutting tool and the type-metal would have thrown the image entirely off the sensitive plate. A singular phenomenon was noticed in this connection. When a comparatively low potential was used, such as that afforded by the air condenser used in our previous investigation, the cutting tool ploughed two or three millimeters along the surface of the type-metal before a spark passed at the point in the circuit where it was desired. With higher potentials this phenomenon was also observed, but the extent of cutting was diminished.

It is possible that that the insulating wax may have melted under the sudden blow of the cutting tool, and, flowing around it, prevented

instant contact. This seems to us improbable, for a deep and clear-cut groove was made in the soft type-metal. Great attention was paid to the solid structure of this contact apparatus. It was entirely separate from the support of the revolving parts, and was perfectly steady.

The other end of the armature shaft was lengthened into a cylindrical chronograph, similar to that described in the article already cited, and its performance left nothing to be desired. A small Ruhmkorf coil, excited by two storage cells, and interrupted by a seconds pendulum, gave a record of the speed of the mirror. The stylus which drew the spiral turns on the barrel of the chronograph was drawn along the barrel by means of a small heavily loaded carriage, which, on being released at the moment the lever arm threw the type-metal in contact with the cutting tool, descended an inclined plane of adjustable height.

A small Töpler Holtz machine charged a large Leyden jar, and it was found to work admirably in all states of the weather. The apparatus which I have thus described was the result of the experience of the previous year, and worked for months without failure; and the taking of photographs of the oscillatory discharge by it became a mere matter of routine.

The following cases were tried: —

(1.) When the long parallel wires were of copper (diameter .087 cm.), the number of double oscillations visible on the negatives averaged quite uniformly 9 or 9.5.

(2.) When the wires were of German silver (diameter .061 cm.), three oscillations were visible.

(3.) But when an annealed iron wire (diameter .087 cm.) was substituted, only the first return oscillation was distinctly visible, with occasionally a trace of the first duplicate discharge.

(4.) On substituting fine copper wire (diameter .027 cm.), five complete oscillations were quite uniformly visible.

(5.) Fine German silver wire (.029 cm.), nickel wire (.019 cm.),* soft iron (.027 cm.), and piano steel wire (.027 cm.), gave but faintly the first return discharge after the pilot spark.

The pilot sparks were in all cases strong.

The single return discharge through the iron wire did not admit of measurement sufficiently accurate to furnish any basis for calculation of its self-induction. The time did not apparently differ, if at all, by

* Obtained by the kindness of Joseph Wharton, Esq., of Philadelphia.

more than fourteen or fifteen per cent. Some general reasoning based upon the number of oscillations may be of interest. It must be acknowledged, however, that this reasoning is open to criticism, although it affords the most plausible explanation. The phenomenon itself is not a doubtful one.

The time of a double oscillation for the large-sized copper wire was .0000020 sec.; for the small copper wire, .0000021 sec. The others as far as could be determined did not differ much from these values, and for this purpose either is sufficiently accurate. Denote by R' the ohmic resistance of the parallel wires to alternating currents of this periodicity; by R, the resistance to steady currents.

$$p = \frac{2\pi}{t} = 3{,}000{,}000 \text{ (practically).}$$

Taking the cases up in order:

(1.) Large copper wire,

$$R = 0.285 \times 10^9$$

and substituting in Lord Rayleigh's formula, $R' = \sqrt{\tfrac{1}{2} p l \mu R}$,

$$R' = 0.66 \times 10^9.$$

(2.) Large German silver wire,

$$R = 9.2 \times 10^9,$$

and substituting in the series

$$R' = R\left\{1 + \frac{1}{12}\frac{p^2 l^2 \mu^2}{R^2} - \frac{1}{180}\frac{p^4 l^4 \mu^4}{R^4} + \dots\right\},$$

$$R' = 9.2 \times 10^9.$$

(3.) Large iron wire,

$$R = 2.5 \times 10^9,$$

and if there is a true time lag, as often stated, such as to prevent action of the magnetic property of the iron, and if on this assumption we make $\mu = 1$,

$$R' = 2.78 \times 10^9.$$

(4.) Fine copper,

$$R = 3.3 \times 10^9,$$

$$R' = 3.5 \times 10^9.$$

(5.) Again, as before, call $\mu = 1$ in iron, nickel, and steel. The length of these circuits was 7.41 meters, the remainder of the 10.20 meters — 2.79 meters — being of copper wire of $R' = 0.94$.

The value of R' in the separate cases, including in each the resistance 0.94 of the copper portion, was as follows: —

Soft iron	15.0×10^9
Piano steel	20.7×10^9
Nickel	30.6×10^9
German silver	23.0×10^9

The ratio of the strengths of successive discharges during the oscillation is given by the function $\epsilon^{\frac{rT}{2L}}$, where r is the ohmic resistance, T the time of a double oscillation, and L the self-induction. The ratio of one discharge to the nth one after it is $\epsilon^{n\frac{rT}{2L}}$. If we assume — and it is a large assumption, but one which perhaps the result will in some measure justify — that the ratio of the strength of the first to the strength of the last visible discharge is more or less a constant, we may make use of the above data. Denote $\frac{T}{2L}$ by A, and call the unknown resistance of the short connecting lead wires and of the spark x. Then will $r = R' + x$, and n will be the number of complete oscillations visible.

Take cases (1) and (2), large copper and large German silver wires: —

$$\epsilon^{n_1 (R'_1 + x) A} = \epsilon^{n_2 (R'_2 + x) A} ;$$

$$n_1 (R'_1 + x) = n_2 (R'_2 + x) ;$$

$$9.5 (0.66 + x) = 3 (9.2 + x) ;$$

$$x = 3.4 \text{ ohms.}$$

Taking cases (1) and (4) similarly,

$$n_1 (R'_1 + x) = n_4 (R'_4 + x) ;$$

$$9.5 (0.66 + x) = 5 (3.5 + x) ;$$

$$x = 2.6 \text{ ohms.}$$

Experiments with other copper wires having R' equal to 3.4 and 1.27 gave 5 and 8 for the values of n respectively, or

$$x = 2.4 \text{ ohms.}$$

The resistance (R') of the lead wires forming part of x was 0.8 ohm, leaving as a possible value for the resistance of the spark about 2 ohms.

If, taking this value of x, we calculate the value of R' necessary to damp out the oscillation in one complete double discharge in the case of the large iron wire, we shall have

$$9.5 (0.66 \times 3) = 1 (R' + 3) ;$$

$$R' = 30 \text{ ohms.}$$

But neglecting the magnetic property of the iron, its calculated resistance to alternating currents of this periodicity was $R' = 2.78$ ohms. This is obviously inadequate, and would point to the conclusion that the oscillation is not, as sometimes stated, too rapid to admit of the magnetic action of the iron.

If we substitute this value $R' = 30$ in the equation

$$R' = \sqrt{\tfrac{1}{2} p l \mu R},$$

we have for the resulting value of the magnetic permeability $\mu = 230$. This lies between the limits $\mu = 103$ and $\mu = 1110$, found by taking the number of oscillations one and a half and one half respectively for the case of the iron wire.

It should be noticed that this estimate of μ necessitates assuming that T and L remain the same within broad limits. Measurements of the single oscillation on the negatives show that this is near enough the case. Part of the more rapid decay of the oscillation in the iron may be well ascribed to the dissipation of energy by hysteresis. While we cannot place much reliance upon an estimate of its value in such a case, — its percentage effect probably increasing rapidly with the decay of the spark, — it is not difficult to show that its influence may be very great.

There still remains the fact, not generally recognized, that, in Leyden jar discharges through iron wires, the magnetic property of the iron has time very materially to modify the character of the spark.

We give an example of the measurement of the half-oscillation which was the only one visible on the photograph of the discharge over iron wires, all the others having been dampened or extinguished by the iron, in comparison with the measurement of the similar half-oscillation on copper wires of the same diameter as the iron wires. The number of oscillations on the copper wires was eight.

The total duration of the discharge on iron wires was only three millionths of a second, while that on similar copper wire was three hundred-thousandths of a second. A steel wire gave the same results as the annealed iron wires.

Comparative Lengths of First Half-oscillation in Millimeters.

Fine Iron Wire.	Fine Copper Wire.
.23	.19
.21	.20
.19	.20
.21	.19

Large Iron Wire.	Large Copper Wire.
.20	.17
.20	.18
.19	.20
.19	.18

I wish to express my deep obligations to my assistant, Mr. W. C. Sabine, for his valuable suggestions and for his skill in the mechanical details of this investigation.

Conclusions.

1. The magnetic permeability of iron wires exercises an important influence upon the decay of electrical oscillations of high frequency. This influence is so great that the oscillations may be reduced to a half-oscillation on a circuit of suitable self-induction and capacity for producing them.

2. It is probable that the time of oscillation on iron wires may be changed. Since we have been able to obtain only a half-oscillation on iron wires, we have not been able to state this law definitely.

3. Currents of high frequency, such as are produced in Leyden jar discharges, therefore magnetize the iron.

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